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SEARCHES AT LEP 1.5

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Abstract

The energy upgrade at LEP allows new regimes to be explored in the search for physics beyond the Standard Model. The searches for new physics using the ALEPH, DELPHI, L3, and OPAL data are described, and the results are presented.

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1 Introduction

As LEP increases energy from the Z peak to the W pair threshold, new opportunities in searches for physics beyond the Standard Model are presented. The LEP 1.5 run, which consists of nearly 6 pb^{-1} of data per experiment at energies of 130 and 136 GeV, gives an opportunity to explore unprecedented energy regimes in e^+e^- collisions for evidence of compositeness, fourth generation fermions, and Supersymmetry.

2 Experimental Aspects of Searches at LEP

Topologically, many signatures for new physics at LEP have similar components and similar detector requirements. Missing energy is at the heart of many searches for new physics, and so accurate energy measurement and detector hermeticity are essential. Tracking and calorimetry for jet reconstruction, and identification of leptons and photons are necessary to reconstruct signatures of new physics.

As LEP moves away from the Z peak, the physics opportunities for search analyses increase, and the search conditions change. Signatures for new physics have lower background from Z decays, and the more exotic backgrounds from four fermion processes, WW and ZZ^*/γ , play an increased role. Although the cross sections are lower than those at LEP 2, the event topologies are very similar to those of signal processes. The highest production cross section comes from two photon events. However, these events normally have characteristics very different from those of signatures for new physics, so they are mostly easily eliminated from search analyses.

Four fermion processes are an important background for searches at LEP, especially for searches for Supersymmetry and the Higgs boson. An understanding of the rate and characteristics of these events is thus essential. At LEP 1.5, the dominant four fermion process comes from the production of an on-shell Z boson and a virtual photon. The OPAL collaboration have reported an excess of four fermion final state events with high multiplicity [1]. The ALEPH Collaboration [2] in an analysis sensitive to both high and low multiplicity four fermion final states, observe rates consistent with Standard Model expectations obtained with the FERMISV program [3]. The results are given in Table 1.

3 Searches for Compositeness

Evidence for compositeness may appear in direct searches for new particles, or through anomalies in Standard Model processes.

Results of searches for single and pair production of excited leptons are reported by ALEPH [4], DELPHI [5], and L3 [6]. Excited leptons usually decay radiatively, which gives a signal topology for pair production of two leptons and two energetic photons. For excited neutrinos, the radiative decay may be forbidden, and in that case, the excited neutrino decays to a lepton and a W, and the signal topologies are determined by the W decays (i.e., combinations of leptons and jets with rates determined by the branching ratios). Efficiencies for the search are typically between 45 and 60%, with the τ^* search having a lower efficiency than e^* and μ^* searches. The production cross section for pair production of excited leptons can be as large as 8 pb, and combined with the high efficiency of the analyses, limits were set on excited lepton masses to nearly the kinematic limit, as shown in Table 2. Single production of excited leptons results in events with two leptons and a photon, $e^+e^- \rightarrow \ell\ell^* \rightarrow \ell\ell\gamma$. The production cross section for this process is low ($\leq 0.2 \text{ pb}$), except for excited electrons, which can have a t-channel enhancement of the cross section. The results of the searches can be interpreted

	OPAL		ALEPH		
	$\mu^+\mu^-\text{q}\bar{\text{q}}$	$e^+e^-\text{q}\bar{\text{q}}$	$\ell^+\ell^-\text{q}\bar{\text{q}}$	$\nu\bar{\nu}\text{ff}$	$\ell^+\ell^-\ell^+\ell^-$
FERMISV	$0.55 \pm_{-0.04}^{+0.04} \pm 0.07$	$0.63 \pm_{-0.06}^{+0.06} \pm 0.10$	2.50 ± 0.18	2.38 ± 0.14	1.62 ± 0.08
bkg.	$0.07 \pm_{-0.03}^{+0.06} \pm 0.01$	$0.09 \pm_{-0.04}^{+0.07} \pm 0.03$	$0.14 \pm_{-0.02}^{+0.11}$	$0.04 \pm_{-0.02}^{+0.08}$	$0.01 \pm_{-0.01}^{+0.08}$
Total Exp.	$1.34 \pm_{-0.08}^{+0.10} \pm 0.17$		$6.69 \pm_{-0.24}^{+0.29}$		
Observed	6		5		

Table 1: *Four fermion events observed by the OPAL and ALEPH collaborations, and Standard Model expectations given by FERMISV and background Monte Carlo. OPAL numbers include statistical and systematic uncertainties, and ALEPH statistical and systematic uncertainties are combined in quadrature.*

	e^*	μ^*	τ^*	$\nu^*(\ell W)$	$e^*(\nu\gamma)$
ALEPH	65.1	65.4	64.7	-	-
DELPHI	63.5	63.5	63.1	-	-
L3	64.7	64.9	64.2	57.3	61.2

Table 2: *Mass limits in GeV for excited leptons from the search for $e^+e^- \rightarrow \ell^*\ell^* \rightarrow \ell\gamma\ell\gamma$. Results are given assuming radiative decays, except for neutrinos, where the decay $\nu^* \rightarrow \ell W$ has also been considered.*

	QED cutoff parameters		95% CL
	Λ_+ (GeV)	Λ_- (GeV)	$M(e^*)$
ALEPH	169	132	137
L3	131	167	129
OPAL	152	143	147

Table 3: *Limits derived from the study of coplanar photon events: QED cutoff limits, Λ_+ and Λ_- , and 95% CL limit on the mass of the excited electron, in GeV.*

as limits on the coupling between excited leptons and their partners, which is related to the compositeness scale, as a function of the mass of the excited lepton.

Events with two coplanar photons can be examined for evidence of compositeness through contact interactions or existence of excited electrons produced in the t-channel. New physics is detectable through deviations in differential cross sections from the Standard Model predictions. Limits can be set on QED cutoff parameters from these comparisons. Also, if the $ee^*\gamma$ and $ee\gamma$ couplings are assumed to be equal, a limit on the mass of the excited electron can be derived. These results are given in Table 3 for the ALEPH [7], L3 [8], and OPAL [9] analyses.

4 Fourth Generation Leptons

Searches for fourth generation leptons are reported by L3 [10]. Charged heavy leptons are pair produced and then decay via a W to their neutral partner, which is stable, massive, and invisible. The experimental topologies are determined by the W branching ratios, as each event will have two W's and two massive invisible particles. The topologies are a pair of leptons, a

lepton and jets, or jets, all with missing energy and mass. No events are selected in the L3 analysis, while 0.9 events are expected from Standard Model background. From the predicted production cross section of 1-4 pb, charged heavy leptons are excluded up to 62 GeV, if the mass difference between the charged and neutral lepton is high enough.

Pair production of neutral heavy leptons which decay via a W to a lower generation lepton is also considered. Topologies determined by the W branching ratios have at least two leptons and jets. In the L3 analysis, 0.9 events were expected in the electron channel and 0.3 in the muon channel, and none were selected in the data. Heavy Dirac neutrinos are excluded for masses up to 58.9 GeV, and Majorana neutrinos up to 48.1 GeV.

ALEPH reports an analysis for t-channel production of a single heavy neutrino and first generation neutrino [4]. Isosinglet heavy neutrinos are predicted in models such as the Seesaw Model. The heavy neutrino decays to a W and first generation lepton, and so the topologies include an electron and the products of the W decay. The degree of mixing between the fourth and first generation determines the cross section, so the result of the analysis is a limit on the amplitude of the mixing, as a function of the mass of the heavy neutrino. Although LEP 1 limits on the mixing amplitude are not exceeded, the mass range is increased.

5 Single Photon Searches

Pair production of neutral stable particles, such as neutrinos or the lightest supersymmetric particle, can not be detected except in the case where an initial state photon is detected. Measurement of the single photon rate was used to set limits on $e^+e^- \rightarrow XX$, where X is any neutral stable particle. The dominant Standard Model process, $e^+e^- \rightarrow \nu\nu\gamma$, is an irreducible background for this signature. The cross sections reported by ALEPH [7], DELPHI [11], and OPAL [9] are consistent with expectations for $e^+e^- \rightarrow \nu\nu\gamma$.

6 Supersymmetry

The Minimal Supersymmetric extension of the Standard Model predicts a supersymmetric partner for all Standard Model particles. This results in a spectrum of new particles. The supersymmetric partners of the charged bosons, \widetilde{W}^\pm and \widetilde{H}^\pm , mix to form two states of charginos, $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^\pm$. The neutral bosons, $\widetilde{\gamma}$, \widetilde{H}^0 , and \widetilde{Z}^0 , mix to form neutralinos, $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_3^0$, and $\widetilde{\chi}_4^0$. The supersymmetric partners of the fermions of the Standard Model are the sleptons, \widetilde{e} , $\widetilde{\mu}$, $\widetilde{\tau}$, and $\widetilde{\nu}$, and the squarks, \widetilde{q} .

R parity, a new quantum number having the value of -1 for supersymmetric particles and +1 for Standard Model particles, is introduced in order to prevent fast proton decay. In the analyses reported here, R parity conservation is assumed. Experimental consequences of this assumption are that SUSY particles are produced in pairs, and the lightest SUSY particle, the LSP, does not decay. The lightest neutralino, $\widetilde{\chi}_1^0$, is massive and neutral, and escapes detection. The signatures for Supersymmetry are events with missing energy and mass, due to the presence of the LSP.

Experimentally, Standard Model processes can mimic the signal when the events have missing energy from initial state radiation, neutrinos, or particles at low angles which are not detected. The search is made more difficult when the mass difference between the next-to-lightest supersymmetric particle (the NLSP) and the LSP is small, since this leads to events which are difficult to detect, and kinematically resemble the two-photon background.

The ALEPH [12], DELPHI [13, 14], L3 [15], and OPAL [16, 17] searches use kinematic properties of the signal in order to differentiate it from the background. The signal, with missing

	ALEPH	DELPHI	L3	OPAL
$M(\tilde{\chi}_1^\pm)$	67.8	66.8	65.0	65.4

Table 4: 95% CL limits on the chargino mass in GeV, assuming $\Delta M(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0) \geq 10$ GeV, and $m_{\tilde{\nu}} \geq 200$ GeV.

energy and mass from the LSP, has large transverse momentum imbalance. Typical Standard Model backgrounds, in particular two-photon processes, have missing momentum parallel to the beam direction, and thus low transverse momentum. Transverse imbalance can also be exploited by the quantity of the scalar sum of the momenta perpendicular to the thrust axis in the transverse plane, which is used in slepton searches against the $\gamma\gamma \rightarrow \tau^+\tau^-$ background. Another distinguishing characteristic is the distribution of energy in the detector, as $\gamma\gamma$ events will have a large fraction of the total visible energy concentrated at low angles. The background from $e^+e^- \rightarrow \gamma Z \rightarrow q\bar{q}\gamma$ can have missing energy due to the ISR photon, a neutrino from a heavy quark semileptonic decay, or mismeasurement. A useful property of the signal is the isolation of the missing momentum vector, projected into the plane transverse to the beam, which allows separation of $q\bar{q}\gamma$ events from the signal. Using kinematic quantities such as these, the LEP analyses are able to obtain very low background expectations, while retaining reasonable signal efficiencies, for mass differences (NLSP-LSP) above 5 GeV.

6.1 Results of Searches for Supersymmetric Particles

Charginos are theoretically favored to be light, and considered to have the highest discovery potential since the predicted cross sections are high (~ 5 -20 pb) and the experimental signatures are clear. The cross section, however, can be decreased by t-channel interference if the sneutrino is light. If the sneutrino is lighter than the chargino, two body decays dominate ($\tilde{\chi}_1^\pm \rightarrow \ell^\pm \tilde{\nu}$). Typically, however, the chargino decays to a neutralino and a W, so the topologies are determined by the W branching ratios. The experimental topologies are: a pair of acoplanar jets, jets and a lepton, and acoplanar leptons, all with missing energy and mass. Efficiencies reported for chargino detection are as high as 74%, for a mass difference ($\tilde{\chi}_1^+ - \tilde{\chi}_1^0$) of 30 GeV, with an expected background of approximately one event. No evidence for chargino production was found, and mass limits were set nearly up to the kinematic limit, as shown in Table 4.

The search for neutralinos is complementary to the chargino search, since the highest neutralino production cross sections (~ 7 pb) occur in the higgsino region, where the chargino selection efficiency is lower due to the near mass degeneracy of the chargino and neutralino. Neutralino searches at LEP 1.5 focused on associated production of $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ where $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$; thus the neutralino signatures are determined by the Z branching ratios, leading to topologies of acoplanar jets or leptons, with missing energy and mass. Efficiencies as high as 30% are attainable when the mass difference ($\tilde{\chi}_2^0 - \tilde{\chi}_1^0$) is 10-15 GeV. No evidence for neutralino production was found by the LEP experiments.

Squarks are usually expected to be too heavy, and the cross section too small, to be of interest for current searches at LEP, except under special circumstances. In the case of the \tilde{t} , large Yukawa coupling leads to large off-diagonal terms in the mass matrix, causing mixing between the left and right states. Thus, there can be a large mass splitting between the two \tilde{t} states, so that the lightest \tilde{t} could be detectable at LEP energies. The production cross section for $e^+e^- \rightarrow \tilde{t}\tilde{t}^*$ depends on the mixing angle. The topology expected for stop decays is a pair of acoplanar jets, as each stop squark decays to a charm quark and a neutralino. Typical search

efficiencies are between 50 and 64%, for a mass difference ($\tilde{t}-\tilde{\chi}_1^0$) of 30 GeV/c². Searches by ALEPH, DELPHI, L3, and OPAL found no candidates, and limits were placed on the stop mass as a function of neutralino mass and mixing angle. In the most optimistic case, where $\Theta_{\text{mix}}=0$ and the production cross section is highest, limits on the \tilde{t} mass of 52-57 GeV are set by the LEP experiments.

The topology for pair production of sleptons, $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^- \rightarrow \ell^+\tilde{\chi}_1^0\ell^-\tilde{\chi}_1^0$ is a pair of acoplanar leptons, accompanied by missing energy and mass. Typical search efficiencies are about 70%, for \tilde{e} 's and $\tilde{\mu}$'s, when the $\tilde{\chi}_1^0$ is ~ 30 GeV lighter than the slepton. Efficiencies fall when the mass difference between the slepton and $\tilde{\chi}_1^0$ decreases, and are generally lower for $\tilde{\tau}$'s. No candidates were selected in the ALEPH and L3 analyses, which expected approximately one event from background processes, and limits can be placed on the slepton mass as a function of neutralino mass. Because the production cross sections for smuons and staus are low (~ 0.5 pb), the limits set at LEP 1 are not improved. However, for selectrons, the production cross section can be enhanced by t-channel neutralino exchange, if the neutralino is light enough and contains a significant gaugino component. In that case, improved limits can be set on the mass of the selectron, to 53 GeV.

The limits on the masses of the supersymmetric particles can be interpreted in the parameter space of the MSSM. Chargino and neutralino masses depend on three parameters; $\tan\beta$, μ , and M_2 . Assuming a heavy $\tilde{\nu}$ ($m_{\tilde{\nu}} \geq 200$ GeV), improved limits on μ and M_2 for two values of $\tan\beta$ are shown in Figure 1.

An interesting result is derived by ALEPH for the combination of LEP 1 and LEP 1.5 results [18]. The mass of the lightest neutralino is not bound for all values of $\tan\beta$ from the LEP 1 or LEP 1.5 results, if taken separately. However, if the results are combined, they complement each other such that the mass of the lightest neutralino is restricted to be ≥ 12.8 GeV, for all $\tan\beta$, as shown in Figure 2.

7 Conclusion

The recent increase of energy at LEP has allowed new regions of parameter space to be explored in the search for new physics. No discoveries are reported in searches for compositeness, fourth generation leptons, and Supersymmetry, but improved exclusion limits are set.

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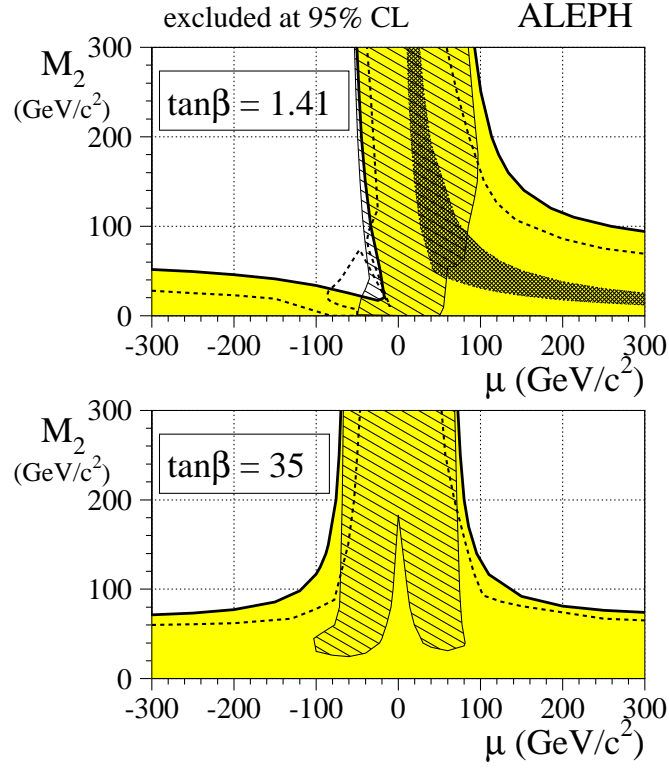


Figure 1: Regions in the $\mu - M_2$ plane excluded by chargino and neutralino searches, for $\tan\beta = 1.41$ and 35 , and $m_{\tilde{\nu}} = 500 \text{ GeV}$. The shaded region is excluded by chargino searches and the hatched region by neutralino searches at LEP 1.5. The dashed lines indicate the LEP 1 limit.

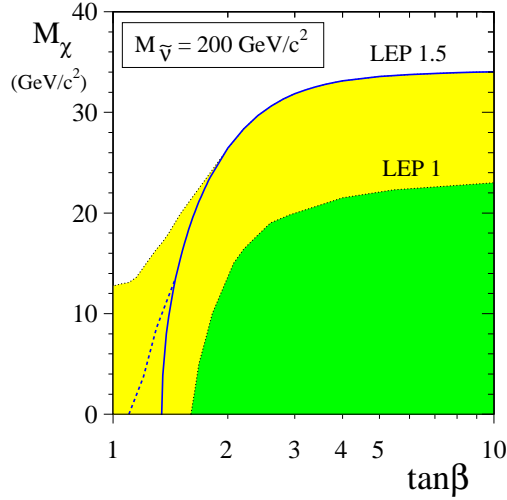


Figure 2: Lower limit on the mass of the lightest neutralino as a function of $\tan\beta$, for $m_{\tilde{\nu}} = 200 \text{ GeV}$, derived by ALEPH. The dark shaded region is the LEP 1 limit. The solid line is the limit from chargino searches, and the dashed line from neutralino searches at LEP 1.5. The light shaded region is the mass of the lightest neutralino excluded by the combination of the LEP 1 and LEP 1.5 limits.